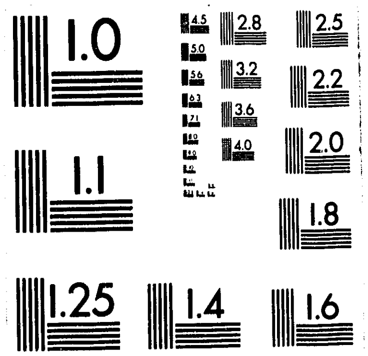
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Combustion Tests of a Turbine Simulator Burning Low Btu Fuel From a Fixed Bed Gasifier

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DISCLAIMER

1.6 Combustion Tests of a Turbine Simulator Burning Low Btu Fuel From a Fixed Bed Gasifier

CONTRACT INFORMATION

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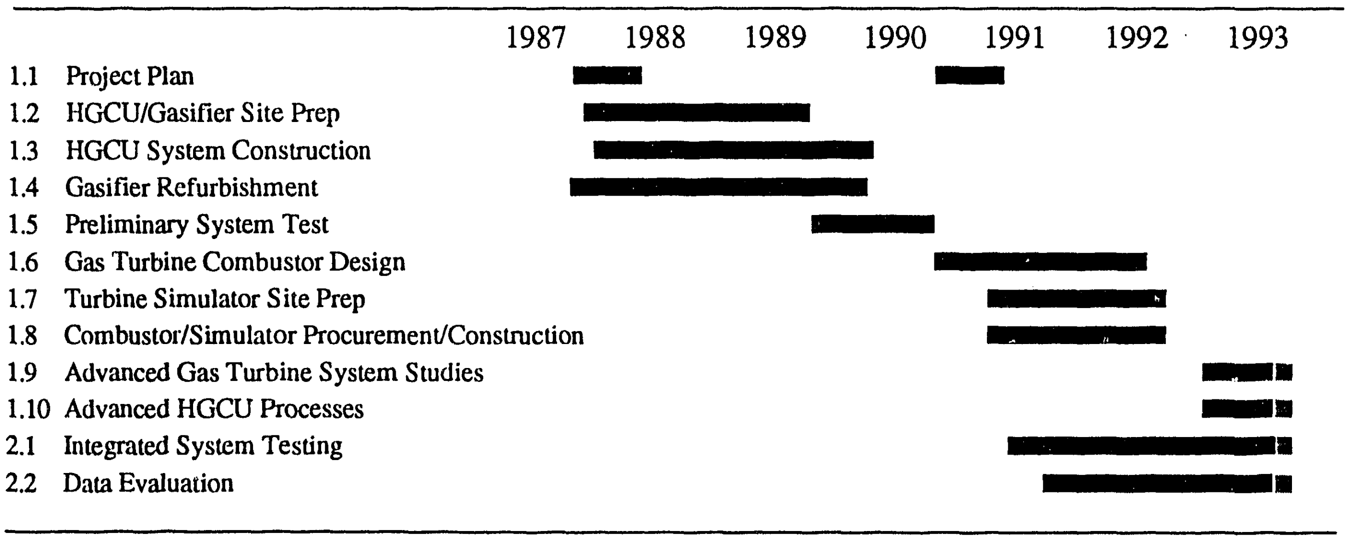
Period of Performance September 30, 1987 to September 30, 1993

Schedule and Milestones

Program Schedule



OBJECTIVES

One of the most efficient and environmentally compatible coal fueled power generation technologies is the integrated gasification combined cycle (IGCC) concept. When IGCC is coupled with high temperature desulfurization, or hot gas cleanup (HGCU), the efficiency and cost advantage of IGCC is further improved with respect to systems based on conventional low temperature gas desulfurization. Commercialization of the IGCC/HGCU concept requires successful development of combustion systems for high temperature low Btu fuel in gas turbines. Toward this goal, a turbine combustion system simulator has been designed, constructed, and fired with high temperature low Btu fuel. Fuel is supplied by a pilot scale fixed bed gasifier and hot gas desulfurization system. The primary objectives of this project are: (1) demonstration of long term operability of the turbine simulator with high temperature low Btu fuel; (2) measurement of NO_x, CO, and particulate emissions; and (3) characterization of particulates in the fuel as well as deposits in the fuel nozzle, combustor, and first stage nozzle.

In a related project, a reduced scale rich-quench-lean (RQL) gas turbine combustor has been designed, constructed, and fired with simulated low Btu fuel. The overall objective of this project is to develop an RQL combustor with lower conversion of fuel bound nitrogen (FBN) to NO_x than a conventional combustor.

BACKGROUND INFORMATION

Combustion of the high temperature (~1000°F) low Btu fuel produced from an IGCC/HGCU system is significantly different from the combustion of typical gas turbine fuels, such as natural gas and fuel oils. Differences in the air/fuel ratio, fuel composition, and fuel temperature affect many of the combustor operating parameters including the lean blowout limit, flame stability, and emissions. These differences require modification of the fuel nozzle and combustor liner. In addition, gas turbines used in IGCC/HGCU applications will require fuel control valves that are capable of operating with high temperature low Btu fuel. Other concerns include the possibility that particles and vapor phase contaminants in the fuel may form deposits on and/or cause the corrosion of the fuel nozzle, combustor liner, and turbine blades.

Rich-quench-lean (RQL) combustion is a well known method for reducing NO_x emissions from the combustion of fuels that contain bound nitrogen. The low Btu fuel produced in an IGCC/HGCU system will contain hundreds to thousands of parts per million of FBN, depending upon the coal composition and the process conditions. In this context FBN refers to all nitrogen-containing compounds other than N_2. The most abundant bound nitrogen species in low Btu fuel is typically NH_3.

A large fraction of the bound nitrogen in the fuel will form NO_x in a conventional combustor. RQL combustion can achieve lower NO_x emissions from fuels containing bound nitrogen because a large fraction of the FBN is converted into non-reactive N_2 on the fuel rich stage. Additional air is introduced on the quench stage, and the lean stage provides the residence time needed to achieve complete combustion.

Although the basic principles of RQL combustion are well known, there are several research issues associated with the development of a practical RQL gas turbine combustor. For example, the optimal air split between the rich and lean stages depends upon many factors, including the fuel composition. The required rich stage residence time is linked to the degree of fuel/air premixing on the rich stage. Increasing the degree of premixing can reduce the rich stage residence time required for low NO_x emissions. The burned gas exiting the rich stage must be quenched rapidly to prevent thermal NO_x formation. For this reason rapid quench methods need to be developed.

PROJECT DESCRIPTION

Turbine Simulator

Figure 1 shows the low Btu gas turbine simulator that has been constructed and integrated with the coal gasification/hot gas cleanup facility at GE Corporate Research and Development in Schenectady NY. The pilot scale gasification/hot gas cleanup system consists of a fixed bed gasifier, a primary cyclone for particulate removal, a moving bed high temperature desulfurization system, and a polishing cyclone. The turbine simulator is designed to operate at the full capacity of the gasifier, 8000 lb./hr of fuel gas from the gasification of 1800 lb./hr of coal. The low Btu fuel is supplied at a pressure of 20 atm and a temperature of 1000°F. A typical fuel composition (after H_2S removal) is given in Table 1. Details of the gasifier and the hot gas cleanup system can be found in Cook *et al.* (1992, 1991).

The turbine simulator includes: a low Btu fuel nozzle; a modified GE MS6000 combustor liner; a film cooled, first stage LM6000 nozzle

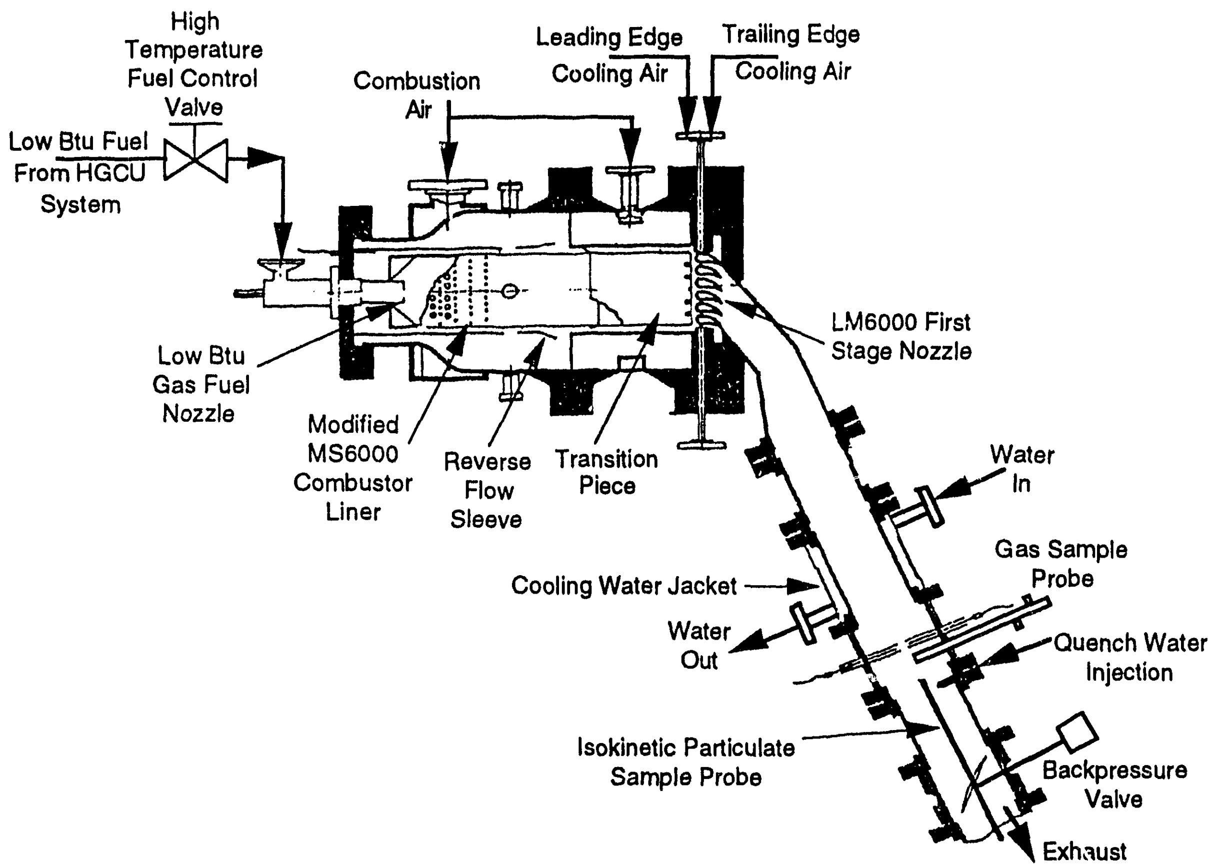


Figure 1. The Turbine Simulator Test Stand

assembly, and an impingement cooled transition piece. A GE MS6000 combustor liner was chosen because its fuel requirements match the capacity of the gasifier/HGCU system. The liner was modified to meet the air requirements of low Btu fuel combustion, while the reverse flow sleeve is standard hardware. The fuel nozzle was designed specifically for low Btu gas combustion (Lawson, 1985). A film cooled LM6000 first stage nozzle was chosen to simulate the film cooled nozzles found in advanced gas turbines with high firing temperatures.

Design of the turbine simulator was initiated in April 1991. Fabrication and assembly were completed in August 1992. The current test plan includes five fired tests with coal gas from the pilot scale gasifier/HGCU system, designated as Runs 3, 3A, 4, 5, and 6. Run 3 was completed in September 1992; Run 3A was completed in February 1993; and Run 4 was conducted in June 1993. Runs 5 and 6 will be completed in the third and fourth quarters of 1993.

Table 1. Typical Pilot Plant Low Btu Fuel Composition

Species	Mole Percent
CO	8.6
H_2	17.3
CH_4	2.7
N_2	30.1
CO_2	12.6
H_2O	28.0
Ar	0.3
NH_3	0.4
TOTAL	100.0

Rich-Quench-Lean (RQL) Combustor

The reduced scale RQL combustor that has been designed and tested with simulated low BTU fuel is shown in Figure 2. Nominal design conditions are 0.75 lb./s total flow, 650°F inlet air temperature, and combustor exit temperatures up to 2500°F. The RQL combustor has a modular design, which allows for rapid evaluation of different hardware configurations. The rich and lean stages are separate components, and the air flow to each stage can be independently varied. Both stages are cooled by reverse flow sleeves. To improve cooling, the rich and lean stage liners have been coated with a ceramic thermal barrier coating on the combustion side. A surface roughness coating and a boundary layer trip wire have also been applied to the backside of each stage.

Design of the RQL combustor began in December 1991. Following construction and assembly, the first fired tests of the RQL combustor with natural gas/nitrogen/ammonia blends began in January 1992. Room temperature natural gas /N_2 /NH_3 blends were chosen for these tests because they simulate some of the characteristics of high temperature low Btu fuel (see Figure 3). A test with high temperature low Btu fuel from the pilot plant gasifier/HGCU system is scheduled for 1993.

RESULTS

Turbine Simulator

The turbine simulator was fired with coal gas for a total of 10 hours during Run 3 and 47 hours during Run 3A. Due to operating problems with the gasifier and HGCU system, the turbine simulator was fired for only 14 hours during Run 4. The gasifier was fueled with Illinois #6 coal for Run 3, while an anthracite coal was used for Run 3A. The use of anthracite for Run 3A was dictated by HGCU system related issues. For Run 4, the gasifier was fueled with Illinois #6 and Crown II coal.

Figure 4 shows the measured combustor exit temperature over a typical time period during run 3A. The initial time in Figure 4 corresponds to 1 AM on the morning of February 10, 1993. Overall, the combustion of low Btu fuel in the turbine simulator was stable and the turbine simulator was easy to control.

The oscillations in temperature shown in Figure 4 ($\pm$ 90°F = $\pm$ 1σ) correlate well with the heating value of the low Btu fuel, which in turn correlates with the position of the stirrer in the fixed bed gasifier. To reduce the temperature fluctuations, the manual fuel control used for Runs 3 and 3A was replaced with an automatic fuel control system for Run 4. Figure 5 shows the measured combustor exit temperature over a typical time period during Run 4. Comparison with Figure 4 shows that the automatic fuel control system substantially reduced the temperature oscillations.

The combustor liner, transition piece, and cascade metal temperatures were all within design limits at full flow conditions. There were periods of low fuel flow during Run 3A, and during these periods the air flow was reduced to maintain high combustor exit temperatures. Combustor liner and transition piece temperatures increased to allowable limits during these transient periods. After Run 3A a small (1 inch diameter) hole was found in the head end of the combustor, and the hole is believed to have been formed during one of the transient periods of low air flow. To solve this problem the combustor liner was modified to increase the air flow through the head end of the combustor. No problems with the modified liner were encountered during Run 4.

Figure 6 shows typical NO_x emissions measured during Run 3A, over the same time period as shown in Figure 4. Over the entire run, NO_x emissions averaged about 180 $\pm$ 20 ppmv on a dry, 15% O_2 basis. CO emissions were generally below the detection limit of 1 ppmv. NO_x emissions were not correlated with firing temperature, suggesting that the majority of the NO_x formed came from the NH_3 and other FBN species in the fuel. The average measured ammonia concentration in the fuel was approximately 2700 ppmv, indicating that the conversion of NH_3 to NO_x was about 39%.

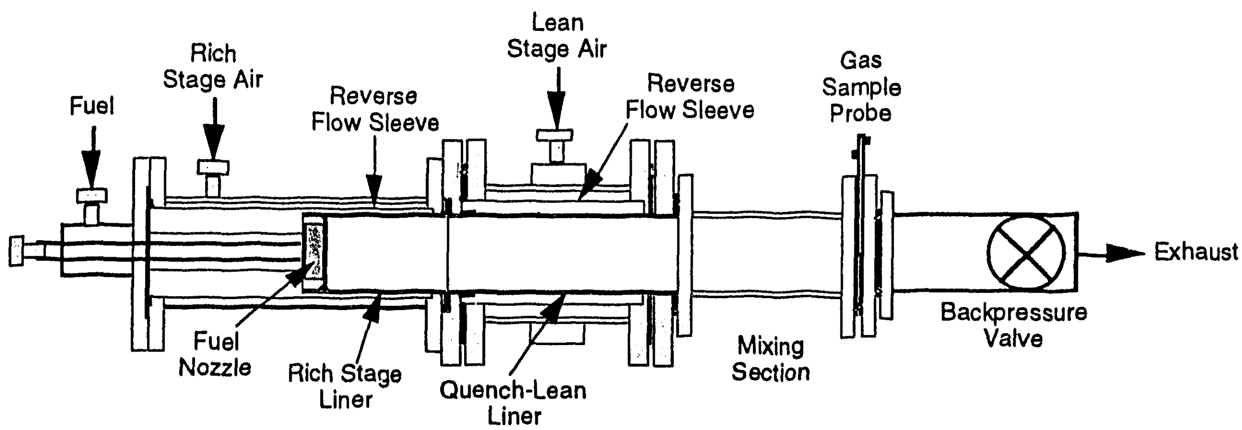


Figure 2. Reduced Scale Rich-Quench-Lean (RQL) Combustor

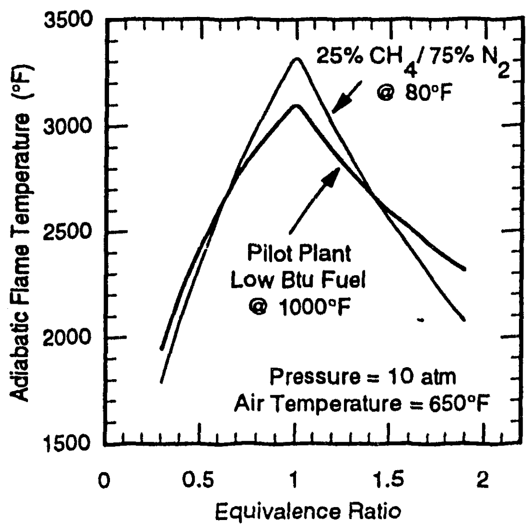


Figure 3. Comparison of Pilot Plant Fuel and Natural Gas/N_2 Blend

The anthracite coal used in Run 3A resulted in abnormally high particulate loadings in the low Btu fuel. When gasifying Illinois #6 coal, particulate loadings of 30 to 40 ppmw are typically found in the low Btu fuel leaving the HGCU system, versus the 200 ppmw found during Run 3A. The high particulate loadings in the fuel resulted in reddish-brown deposits on the combustor liner, transition piece, and cascade. Elemental analysis revealed that the composition of the deposits was similar to the composition of the coal ash. The relatively high deposition rate seen in Run 3A is not representative of the deposition rate expected in a commercial IGCC/HGCU power plant equipped with a barrier filter just upstream of the combustor.

Although a barrier filter can remove particulates in the fuel with high efficiency, it may have little effect on the concentrations of vapor-phase contaminants. Vapor-phase levels of alkali metal species are of particular interest, since alkali metals are the principal agents of hot corrosion. To address this issue we have used thermodynamic equilibrium to calculate maximum expected vapor-phase alkali metal levels in hot coal gas. The calculations were performed with a slightly modified version of the NASA chemical equilibrium program (Gordon and McBride, 1976; McBride, 1989). The coal gas composition listed in Table 1 was used for the calculations, with the addition of 200 ppmv HCl, 50 ppmv of H_2S, and sufficient amounts of sodium and potassium to insure the existence of condensed sodium and potassium species in the equilibrium mix.

The two principal sources of thermodynamic data were the JANAF Thermochemical Tables (Chase *et al.*, 1985) and the extensive compilation of Barin (1989). In addition to all of the major carbon-, hydrogen-, oxygen-, nitrogen-, and sulfur-containing species, some 60 solid, liquid, and vapor sodium and potassium species were considered. In particular, the alkali cyanides, chlorides, hydrides, carbonates, oxides, hydroxides, sulfides, and sulfates were included in the calculations. Solid carbon (coke) was excluded from the equilibrium composition, based upon kinetic constraints.

Table 2 lists the calculated vapor-phase alkali metal concentrations at coal gas temperatures of 1000°F and 1200°F. Only the most abundant alkali metal species are listed in Table 2; all other alkali metal species were present in the vapor phase at concentrations below 0.1 ppb by weight as Na or K. At 1000°F, the total vapor-phase alkali species levels are well within gas turbine limits. At this temperature, the bulk of the sodium is predicted to exist in the solid phase as sodium carbonate (Na_2CO_3), and the bulk of the potassium is predicted to exist in the solid phase as potassium cyanide (KCN). As the temperature increases, vapor phase sodium and potassium chloride concentrations increase dramatically. Note that both NaCl and KCl dimerize in the vapor phase, and that the contributions of $(NaCl)_2$ and $(KCl)_2$ are significant.

Sodium and potassium silicates and aluminates were not included in the thermodynamic calculations. If these species were included, the predicted vapor phase concentrations of sodium and potassium species would be significantly reduced. For this reason, the values listed in Table 2 probably overestimate the actual vapor phase concentrations of alkali species.

Rich-Quench-Lean (RQL) Combustor

Typical NO_x and CO emissions from the RQL combustor are shown in Figure 7. For this test the fuel was a blend of natural gas and nitrogen (25.0 volume percent natural gas, 75.0 volume percent nitrogen), and contained no ammonia. The rich stage air temperature was not identical to the lean stage air temperature because the two stages are fed by two separate air lines with different diameters and different heat losses. The rich stage and lean stage air flow rates were held constant as the total fuel flow rate was varied. In this manner the ratio of the rich stage equivalence ratio (φ_{rich}) to the lean stage equivalence ratio (φ_{lean}) was held constant. A practical RQL gas turbine combustor will probably have to operate at a fixed air split, that is, a fixed $\varphi_{lean}/\varphi_{rich}$.

Complete combustion (CO less than 1 ppmv) was achieved under almost all conditions, as long as the lean stage temperature was greater than 1800°F. As the lean stage temperature decreased below about 1750°F, CO increased sharply. A sharp increase in CO emissions as burned gas temperature decreases is commonly observed near blowout. In this case the lean stage was approaching blowout, even though the rich stage was still lit and far from blowout.

Figure 7 shows that NO_x emissions are very sensitive to the air split between the rich and lean stages, or $\varphi_{lean}/\varphi_{rich}$. This result was expected from previous experimental work and chemical kinetic modeling (Goebel and Feitelberg, 1992). Figure 7 also shows that NO_x emissions decrease monotonically as the combustor exit temperature decreases. Previous work suggested that there should be a minimum in NO_x emissions in Figure 7, that is, an optimum φ_{rich}. The most probable reason for the difference between these results and the previous work is the structure of the rich stage flame. In the previous work, and in the chemical kinetic models, the rich stage flame was premixed. The scaled down low Btu fuel nozzle used in these tests creates a diffusion flame. While a diffusion flame is advantageous from a

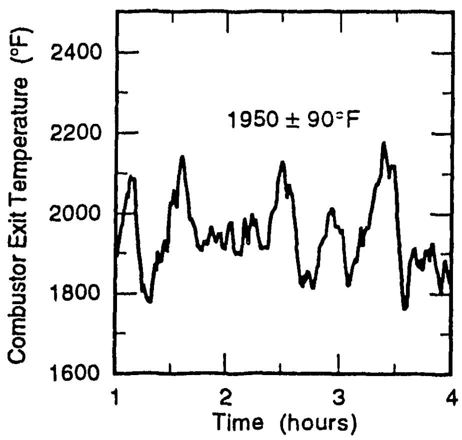


Figure 4. Typical Turbine Simulator Temperatures From Run 3A

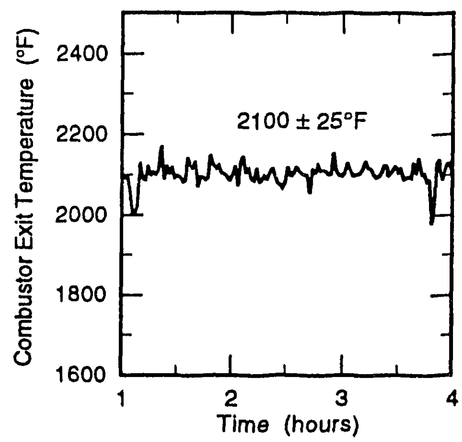


Figure 5. Typical Turbine Simulator Temperatures From Run 4

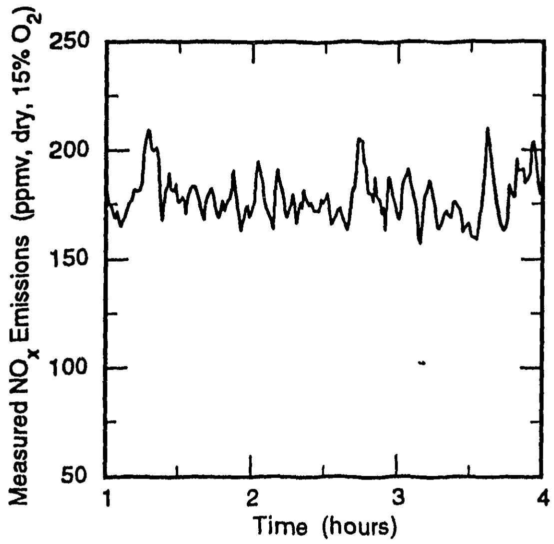


Figure 6. Typical Turbine Simulator NO_x Emissions From Run 3A

flame stability and flame dynamics point of view, a premixed flame is advantageous from a low NO_x emissions point of view. A premixing rich stage fuel nozzle should significantly reduce NO_x emissions.

With no ammonia in the fuel, the best performance achieved to date is less than 10 ppmv NO_x (on a dry, 15% O_2 basis) at a combustor exit temperature of 2350°F, using the long rich stage liner. Increasing the rich stage residence time significantly reduces NO_x emissions. Given sufficient rich stage residence time, NO_x emissions are relatively insensitive to the flow split between the rich and lean stages (that is, $\varphi_{lean}/\varphi_{rich}$). Increasing the rich stage residence time had little effect on CO emissions.

Measurements of NO_x emissions without ammonia in the fuel establish a baseline of performance for the RQL combustor. These measurements are also an indication of the effectiveness of the quench section design. Rapid quenching will result in low NO_x emissions, while slow quenching will result in high NO_x emissions. Note that the stoichiometric flame temperature of this natural gas/nitrogen blend is more than 200°F higher than the stoichiometric flame temperature of a typical low Btu fuel (see Figure 3). These results demonstrate the effectiveness of the quench stage design.

Similar tests were conducted with ammonia added to the natural gas/N_2 fuel blend. NO_x emissions and the conversion of NH_3 to NO_x have been higher than expected. With 2800 to 3500 ppmv NH_3 in the fuel, the conversion of

Table 2. Calculated Equilibrium Levels of Alkali Species in Low Btu Fuel

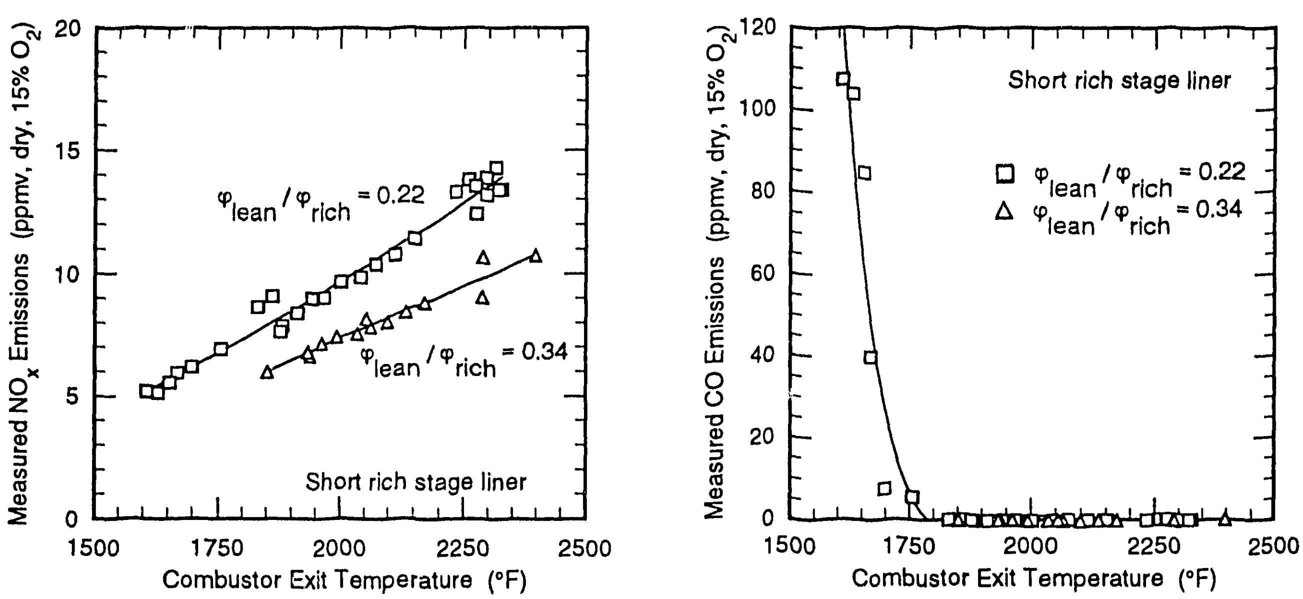
	Gas Phase Concentration (ppb by weight as Na or K)	
Gas Phase Species	T = 1000°F	T = 1200°F
Na	< 0.1	< 0.1
NaCl	4.3	225
NaOH	< 0.1	0.5
$(NaCl)_2$	1.9	145
K	< 0.1	< 0.1
KCl	< 0.1	920
KOH	< 0.1	22
$(KCl)_2$	< 0.1	580

ammonia to NO_x ranged from 35% at low firing temperatures to 55% at high firing temperatures. These tests were conducted over a range of flow splits ($0.21 < \varphi_{lean}/\varphi_{rich} < 0.30$). Doubling the rich stage residence time had little effect on NO_x emissions with ammonia in the fuel. The expected minimum in the conversion of ammonia to NO_x was not observed. In a series of tests conducted with low ammonia concentrations in the fuel (125 to 165 ppmv NH_3), the conversion of NH_3 to NO_x was about 90%. The addition of ammonia to the fuel had little effect on measured CO emissions.

The use of a diffusion flame fuel nozzle is believed to be the reason for the relatively high conversion of NH_3 to NO_x. With a rich stage diffusion flame, NH_3 can convert to NO_x at the stoichiometric fuel/air interface. Although NO_x is destroyed in the rich stage, a very long rich stage residence time is required for low NO_x emissions, because NO_x destruction rates are slower than NH_3 destruction rates. A premixed rich stage flame should avoid this problem. Rich stage residence times on the order of 1 second may be required if the rich stage flame is a diffusion flame, versus 0.1 seconds if the rich stage flame is premixed. A premixing rich stage fuel nozzle, suitable for low Btu fuel applications, is currently being developed.

FUTURE WORK

Two additional long duration tests of the turbine simulator are scheduled for 1993. Deposits on the fuel nozzle, combustor liner, and cascade will be characterized, along with particulates in the fuel and the burned gas. Future tests will also be conducted at higher turbine inlet temperatures



Pressure:	10 atm
Fuel:	25% NG / 75% N_2, 80°F, no NH_3

Lean stage air:	0.37 lb./s, 645°F
Rich stage air:	0.10 lb./s, 525°F (□)
	or 0.19 lb./s, 610°F (Δ)

Figure 7. Typical Emissions From the RQL Combustor With no FBN in the Fuel Left: NO_x Emissions. Right: CO Emissions.

than Run 3A. The objective of these tests will be to simulate "F" machine conditions (turbine inlet temperature = 2350°F).

RQL combustor tests with natural gas/nitrogen/ammonia blends are nearing complete. Remaining tests include evaluation of a premixing fuel nozzle and tests of an improved quench section design.

An RQL combustion test with a slip stream of high temperature low Btu fuel from the pilot plant gasifier/HGCU system is scheduled for 1993. The information gathered from these tests will be used to design a larger scale (turbine simulator scale) RQL combustor.

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